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The acoustical development of the guitar*

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INTRODUCTION

In the same way that musical compositions and musical tastes vary from generation to generation, musical instruments themselves are in a continual state of development. Makers modify instruments in an attempt to "perfect" their sound quality or perhaps to make them more suitable for contemporary concert-hall environments. Players may demand change to improve an instrument's reliability, its ease of playing or to widen its tonal possibilities. Rather like the day-to-day development of children which goes unseen by a parent but which is immediately noticed by a more distant relative whom we rarely see, most changes to instruments are very small and go virtually unnoticed. A broader historical perspective, however, tends to identify specific major events in the development of an instrument. These are usually the result of technological advances in materials or manufacturing techniques, and the rationale behind these innovations is usually evident, at least retrospectively. Change is not necessarily for the better, nor is it always perceived as being desirable, and it will always remain a highly controversial and emotive subject. For example, synthetic materials currently used in the manufacture of strings have increased their reliability, accuracy and the power output of instruments. But there are many players who would deny these advantages claiming that the particular sound produced by gut stringing is a more-desirable quality. Change rarely affects only one aspect of the instrument; more usually there are trade-offs between a number of different quality factors of the instrument.

We can examine the development of the modern guitar in a number of different ways. Rather than taking the broad historical perspective, which tends to identify only major change, this paper seeks an alternative route which will concentrate on understanding how the instrument works at a fundamental level so that the effects of changes, however small, can be objectively assessed. This paper will thus describe the acoustical features that are involved in sound production on guitars, in both their modern and earlier forms. This analytical approach to the understanding of basic acoustics enables the reader to analyze perceived changes in sound quality and relate them to measurable changes in the structure of the instruments or to differences in materials.

The paper will be divided into a number of sections. It will first present a brief overview of how the instrument works acoustically. It will then give a detailed analysis of the sound signal radiated by the instrument with a view to comprehending how the vibrations of the body of the guitar and their radiation fields affect the sound quality of the instrument. The paper will conclude by looking at some specific case studies of important developments as well as commenting on current and possible future developments of the guitar. The paper will tend to address developments to the structure of the instrument rather than playing techniques, and as such it is aimed more at the maker rather than the player, though the latter should find much of relevance.

Although the subject matter underlying this paper is highly technical, I have attempted to minimize the use of technical terms. For readers wishing to pursue the subject further, I have included a bibliography that includes reference to some introductory books [1] [2] [3], as well as to technical articles. One technical term which is essential is frequency. The frequency of a vibration is simply the number of vibration cycles per second (or Hertz). Figure 1 shows a table comparing frequency and pitch. Note that the playing range of the modern guitar goes from just under 100 Hz to about 1000 Hz, though all plucked notes on the guitar contain frequencies up to 20,000 Hz, which is the upper limit of human hearing.

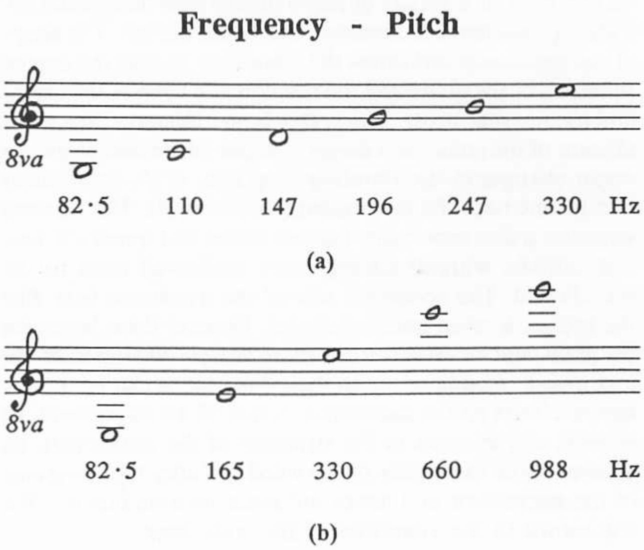

Figure 1. Fundamental frequencies of (a) the open strings of a guitar, and (b) the full playing range of the instrument. All notes also include higher harmonics with frequencies extending to the upper limit of human hearing (20,000 Hz).

THE ACOUSTICAL FUNCTION OF THE GUITAR

The string is the source of the sound, or, more accurately, the source of the vibrations which act upon the air to create the sound. The motion of the string is comparatively large and clearly visible, but the sound radiated directly by the string is practically inaudible. This is because the diameter of the string is very small and it cannot push around enough air to

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create the pressure changes which generate audible sound. As the string vibrates, it pulls and pushes on the bridge, and it is this oscillating force that causes the body to vibrate in sympathy with the strings. Although the motion of the plates (the soundboard and back plate) is very small, their large area ensures efficient coupling to the air. It is these vibrations of the wooden structure which generate the sound we hear. After the string has been plucked, the energy dies away. Much of this energy is lost through friction with just a tiny fraction converted to useful sound.

The player has considerable scope to modify the sound of an instrument. This is achieved by plucking the string at different points or releasing the string in different directions. Altering the amounts of nail and flesh used in the attack can also have a substantial effect on the tone. However, the intrinsic tone quality of a stringed instrument depends on the precise form of the vibrations of the body which are set in motion by the vibrating strings. The exact forms of these vibrations are governed partly by the mechanical properties of the materials used in the construction of the instrument and partly by the dimensions of its constituent parts. The soundboard is undoubtedly the single most important part of the instrument. Makers choose materials for soundboards very carefully, ensuring that they have inherently high stiffness and low density, two factors which combine to enhance the amount of sound radiated from the instrument. Materials for other parts are less critical acoustically; these materials are chosen to fulfill a variety of requirements such as dimensional stability, resistance to abrasion and visual beauty. The shape of the instrument influences the vibrations, as does the precise thickness of the plates and the position and form of the bridge and the internal struts. The bridge is an extremely important element of the guitar, and design changes can be used to induce major changes in the vibrating properties of the instrument and to fine-tune the instrument's response [4]. The internal structure is also important. The fan braces and transverse bars add stiffness without adding much additional mass to the soundboard. The acoustical role of the transverse bars, like the bridge, is often underestimated. Because these lie across the grain, and hence across the more flexible dimension of the instrument, modifications to their dimensions can have very radical effects on the mechanical action of the instrument. In general, any changes to the structure of the instrument, its dimensions or the quality of the wood will alter the vibrations of the instrument and hence influence its tone quality. We will return to the vibrations of the body later.

THE STRUCTURE OF A GUITAR SOUND

There are a number of subjective terms which are commonly used to describe musical sounds. Notes have a certain pitch, loudness and duration, and different instruments are characterized by having different *timbres* or tone qualities. The fact that these terms are *subjective* is a major problem, because there is no consistency amongst individuals in their use of words to describe the same stimulus. A term such as "bright tone" might be meant to convey commendation or condemnation depending on the semantic background of the speaker. There are more fundamental problems also. No two notes, even of the same pitch, played on an individual instrument have the same tone quality. There is, therefore, no exact definition of a "guitar sound." So the assessment of overall quality of an instrument is a complex equation involving the player's reaction to the timbre and variation in timbre from note to note, as well as his reaction to the general ease with which the instrument can be played, its physical balance and its appearance. There is, of course, no thing as a "perfect" instrument because each player uses very different criteria for his choice of instrument.

To proceed further with our acoustical description of the instrument, however, we must have some objective method for describing the sound of a guitar. When the string is plucked, the string and body begin to vibrate. These induce pressure variations in the surrounding air, which radiate as sound waves either directly to the listener's ear or via reflections from the walls, floor and ceiling of the room. Most of the perceived sound signals come via this latter route; hence the acoustics of the room have a large influence on the sound of an instrument. The waves impinging on the ear create a time-varying sound signal which is converted to nerve impulses and sent to the brain. The brain has a remarkable capacity for "analyzing" these signals, which it does by complex processes of *pattern recognition*, that is, comparing what it hears now with a large array of similar patterns it has previously analyzed. Recognition is, therefore, based upon previous experience. It is for this reason that musicians can learn to increase their pitch selectivity or general aural acuity, and it is worth noting that it is this reliance upon previous experience which makes us reluctant to accept change!

Although electronic and computer techniques cannot mimic the analytic techniques or power of the brain, they nevertheless provide us with a method for "visualizing" sounds. This is readily done in the form of a spectrum of the sound. In describing a sound spectrum, it is useful to draw an analogy with a "visual" spectrum. A color television picture is, in fact, made of just three primary colors (red, green and blue). Because of the particular way in which the eye works, when these three colors are mixed together in the correct proportions, they can be used to *synthesize* any hue of any color. We can, of course, perform the reverse process and *analyze* complex colors into their primary constituents. A graph which shows the relative proportions of each color would be called a spectrum. Figure 2 shows sound spectra for three notes on a guitar. Three axes are required; one to show the intensity (loudness) of the components of the sound, one to show what frequencies are present in the sound, and a third axis to show how these two quantities vary with time.

In each of the spectra we see a number of tall peaks which fall in height as time progresses. Each of these peaks occurs at a particular frequency. Most of the peaks occur at frequencies which are almost exactly integer multiples of the fundamental frequency of the string. These are the *harmonics* of the string. The dynamics of plucked strings are discussed in many basic acoustics texts. The motion is more complex than it appears from casual examination of the envelope of a vibrating string. The bending waves induced by plucking travel round the string repeatedly. The repetition rate of the waves depends on the length, tension and mass per unit length of the string. The inverse of the repetition rate is the fundamental frequency of the string, and it is this which governs the *pitch* of the note. However, even though there is but one pitch associated with the sound, we see clearly that the string simultaneously excites vibrations at a large number of higher frequencies. Thus the first string, which has a fundamental frequency of 330 Hz, causes excitation in the

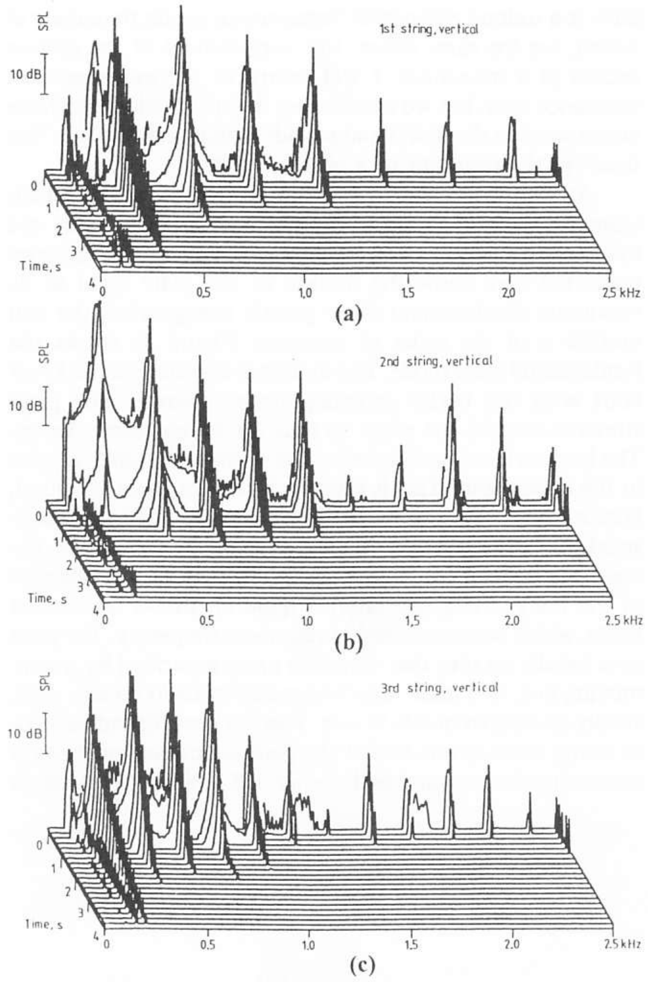


Figure 2. Sound spectra of (a) the first string, (b) the second string and (c) the third string. In each case the string was plucked about one seventh of the way along the string so that it vibrated perpendicular to the soundboard. The vertical axis shows intensity, the horizontal axis shows frequency, and the axis towards the reader shows time.

body of the instrument at 330 Hz, 660 Hz, 990 Hz, 1320 Hz, etc. Harmonic frequencies are very special, because the ear blends the individual sounds to give the perception of one note, with one pitch and a timbre which is related to the relative intensities of the harmonics.

All stringed (and wind) instruments produce harmonics, so it is not the presence of harmonics, nor any particular harmonic structure (the relative intensities of the harmonics), which distinguishes these notes as guitar notes. More important for our perception is the way in which each harmonic starts and decays. The player can put energy into the string only at the beginning of the note, when he stretches the string during plucking. When the string is released it begins to vibrate and it then continually loses energy. Energy losses include friction within the string itself, air friction as the string cuts its way through the air, and energy lost to the body. Only the latter constitutes an efficient use of energy, and even then only a tiny fraction of this vibrational energy is actually converted to audible sound. Frictional losses produce greater effects at higher frequencies. Figure 2 shows very clearly that in general the higher harmonics decay more quickly than the lower harmonics. A simple experiment with a long-duration bass string will demonstrate how the tone of the note becomes more mellow as time progresses and the higher harmonics gradually drop out of the note. There are, of course, some notable exceptions. The fundamental (the first harmonic) in Figure 2b decays away extremely quickly. In this case, the string harmonic happens to have coincided with a resonance of the body (see next section). Under these circumstances, the vibrational energy of the string at that frequency is transferred efficiently into sound and radiated very quickly. This would be perceived as a loud sound but with a short duration. Most guitars have several notes like this, often found somewhere at the lower positions of the fourth string.

A more careful analysis of these figures shows that the major peaks do not occur exactly at harmonic frequencies. There are two primary reasons for this. Firstly, the larger diameter strings are rather stiff, and stiffness affects the way in which the string bends and leads to a progressive sharpening of the "harmonics." (Strictly speaking, the term harmonic should be reserved for frequencies at exact integer multiples, but it is more convenient here to use the term more loosely to describe the frequency components generated by the string.) The "false" sound created by the "harmonics" beings slightly out of tune is particularly noticeable in unwound (plain) third strings. The lower strings, which require even larger mass per unit length, could be made from progressively thicker solid filaments, but because of this problem of *anharmonicity* their sound would then be totally unacceptable. This is why bass strings are made by wrapping wire around a flexible core; the windings maintain flexibility whilst allowing the mass of the string to increase. The second effect which throws the "harmonics" out of tune occurs because of coupling between the vibrations of the strings and the vibrations of the body (see next section). Over coupling can lead to very unpleasant sound quality. The more compliant the body becomes, the more obvious this effect becomes. It is somewhat of a dilemma that strong response of the body, a feature which is necessarily a characteristic of a better quality instrument, also leads to the generation of individual notes of inherently poor sound.

So far, we have identified only the more obvious peaks on the spectra. Careful scrutiny of Figure 2 shows that in addition there are other low-frequency peaks which occur at the beginning of each note. When the player pulls the string aside, he deforms the body of the guitar. When the string is released it takes a little time for the strings' vibrations to build up and communicate with the guitar's body. During this time, however, the distortions induced in the body relax, and in doing so they emit a complex mixture of sounds which are characteristic of the mechanical action of the body itself. An equivalent sound can be produced by damping the strings and tapping the bridge. This tapping noise is not "harmonious" like the string sound. It is, nevertheless, an essential feature of a plucked note and is important for the recognition of an individual instrument. The whole subject of body vibrations will be dealt with in the following section.

BODY VIBRATIONS AND SOUND RADIATION

The strings themselves and the way they are plucked influence the relative intensities and decay rates of the components which we see in the spectrum, but to a large extent they are controlled by the resonances, or vibrations, of the instrument's body. If we are to understand the differences between instruments, therefore, we must investigate further the vibrational properties of the body, the way in which the strings couple to the vibrations and the way in which the body radiates sound to the listener.

In my own research laboratory in Cardiff we use two different techniques to look at the vibrations of instruments. We can do this by performing calculations on a large computer to generate computer graphics of the different modes of vibration of the soundboard and back plate [5]. Alternatively, we can use an optical method to study the actual vibrations of real instruments.

It is perhaps easiest to start with the computer simulations because the output is highly visual and the exaggerated motion is readily understood. The motion of the body of the guitar induced by the string is, in fact, highly complex and varies with time. However, we noted earlier with the string that its motion could by analyzed into a series of more simple vibrations, in that case each with frequencies which were simple multiples of the fundamental motion of the string. Similarly, we can break down the complex motion of the instrument into its individual *modes of vibration*. Any observed motion can be regarded as a simple sum of these modes, driven at the correct frequencies and with the correct relative amplitudes. Figure 3 shows the first five modes of vibration of a soundboard. Each of these motions will be present at any excitation frequency, but each has associated with it a unique *resonance frequency* or *mode frequency* at which, for the same effort, the displacement of the motion occurs at a maximum. I will return to the importance of resonance later, but we should note that the mode frequencies correspond to the individual sounds which make up the "tap tone" in the transient of a plucked note.

At the conference, I demonstrated a video which animated various modes of the guitar. These direct the eye to interesting bending and twisting of the plate. The cartoons presented here show the motion of the plate fixed at its maximum displacement (very greatly exaggerated; the real motion is of the order of microns). Figure 3a shows the fundamental plate mode. The motion is centered on the lower bout with the bridge swinging up and down. The plate stretches around the edges so that the bridge barely bends. The lower transverse bar (below the sound-hole) limits motion in the upper bout. This is a very efficient radiator of sound, because it pushes and pulls the air like the cone of a loudspeaker, inducing large volume changes in the air. In the complete instrument, this mode is affected by the presence of the body cavity (see later). Figure 3b shows the second mode, which occurs at a higher resonance frequency. The plate now breaks up into two vibrating areas separated by a non-moving line, or a *node*. The bridge still tends to remain rigid, simply rocking from side to side. This is a less efficient radiator of sound because one half of the plate is pushing air forward (increasing the pressure) as the other half is pulling the air back

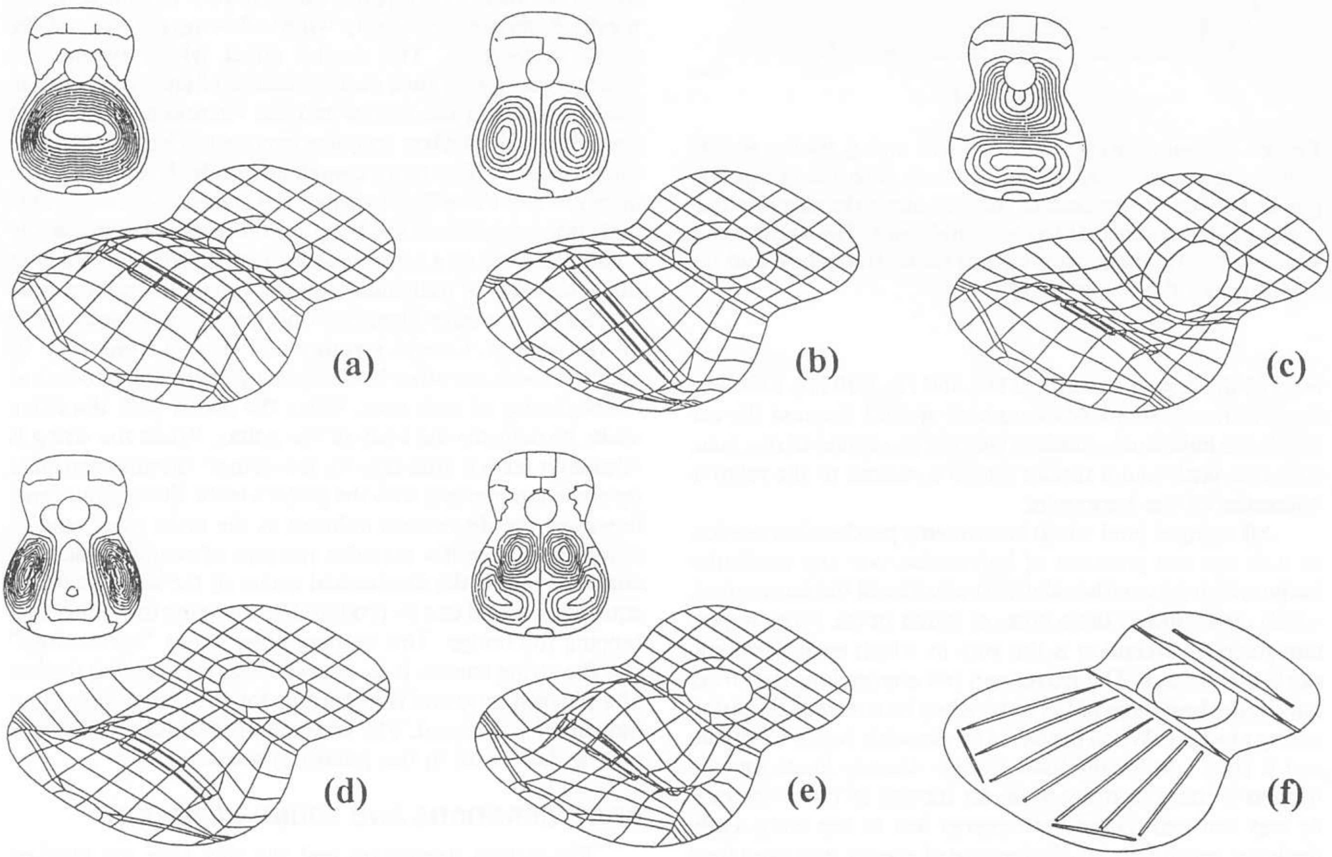


Figure 3. Contour and relief plots of the first five modes of vibration of a guitar soundboard. These modes were calculated using the finite element method from information relating to the material properties and construction of the plate. The internal strutting is shown in the figure at the bottom right.

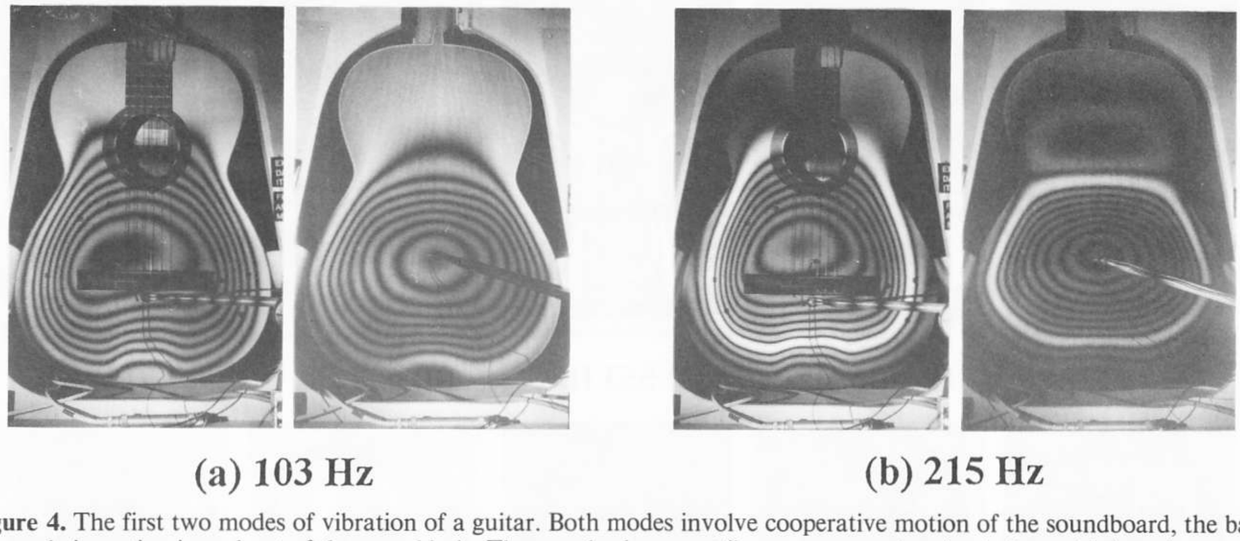


Figure 4. The first two modes of vibration of a guitar. Both modes involve cooperative motion of the soundboard, the back plate and air motion in and out of the sound-hole. These and subsequent figures were made using holographic interferometry.

(decreasing the pressure). There is thus a reduced radiation of energy even though the plate excursions might be large. At a still higher frequency (Figure 3c), the plate divides across the instrument with a nodal line which tends to run across the bridge area. Good construction ensures that the node does not run directly under the strings, because under these circumstances the strings are unable to couple to this mode. This mode is also a strong radiator, simply because the motion in the upper bout is much larger than that in the lower bout so that there is a net volume change, and the criterion for efficient radiation is that there should be a net volume change of the body. It is interesting to note that the lower transverse bar is at the center of the vibrations in the upper bout. Modifications to the dimensions of this bar can induce dramatic changes both to the shape of this mode and its resonance frequency [6]. Similarly, the next mode (Figure 3d) is also a good radiator, because again there is a net volume change in the body. The bridge is now starting to bend, and modifications to its shape can be used to adjust this mode relative to its neighbors. Some of our recent research has shown conclusively that the first, third and fourth modes are responsible for much of the sound radiation from the guitar at all frequencies [7]. Understanding how construction affects the shape and frequencies of these modes is clearly important. At progressively higher frequencies the plate splits into smaller and smaller areas and the vibrations involve a large amount of twisting. These modes are poorer radiators.

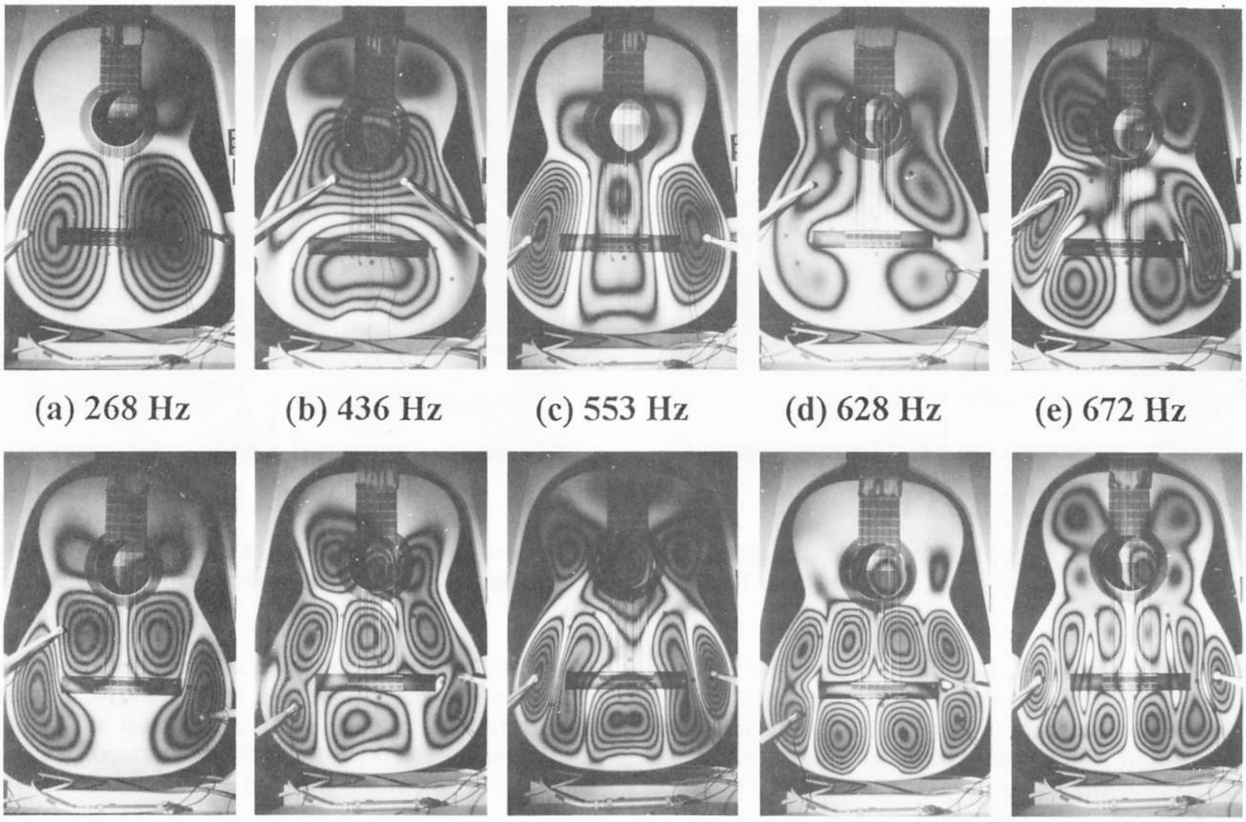
The vibrations of real instruments can be examined using a variety of techniques. Holographic interferometry is an optical method which generates "contour" plots of the vibrations (rather like map contours). The system used in Cardiff is highly sensitive and is capable of detecting the tiny vibration amplitudes found in real stringed instruments. It uses a high-powered laser to make a hologram of the vibrating guitar. Figures 4, 5 and 6 show typical sets of data from an instrument. For example, in Figure 4a we see the guitar overlaid with dark and light bands, which in this case show that the center of the plate is vibrating backwards and forwards (refer to Figure 3a).

Figures 4, 5 and 6 were derived from measurements made on a modern guitar built to a "standard" design [8]. The resonance frequencies, displayed below each mode, are particular to this instrument, but they are typical of most instruments of comparable size. We might also note that there is a surprising similarity between the mode shapes of different guitars, but remember that the precise detail can make enormous differences in the sound.

Figure 4a shows the first resonance, which occurs at about 100 Hz. The whole surface of the plate is vibrating backwards and forwards. The figure includes photographs of both the soundboard and the back plate. Both plates vibrate in a similar manner. In fact, the whole body is vibrating and there is strong cooperation between the soundboard, the back plate and also the air inside the cavity. The body swells and contracts like a balloon producing very efficient sound radiation not only from the plates but also from the air which is forced resonantly in and out of the sound-hole. The frequency of this mode can be controlled to a large extent by the volume of the air cavity (depth of ribs and plate area) and the size of the sound-hole, though the general compliance of both plates is also important. The coupling between the plates and air-cavity resonance extends the response of the instrument at low frequencies [9].

About one octave above, at 215 Hz, the body exhibits similar motion except that the two plates now swing in the same direciton so that the body bends like a thick sandwich (Figure 4b). The node has moved from its previous position on the ribs to a circular region inset from the edge of the plate. We conclude, therefore, that the ribs are in motion and swing in the opposite direction to the center of the plate. This corporate motion of the body is the strongest of all sound radiators.

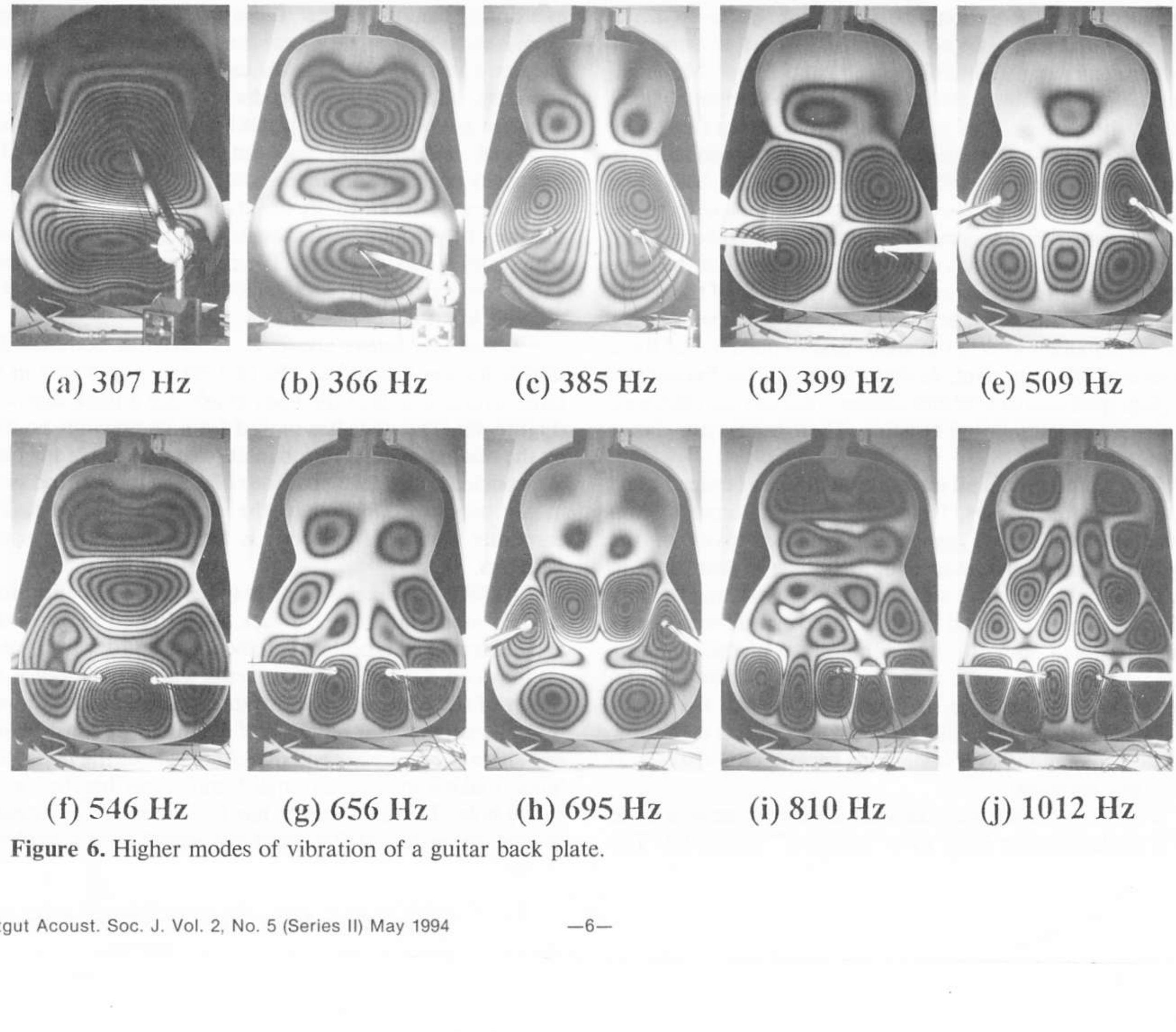
At high frequencies, the vibrations tend to localize either on the soundboard or on the back plate. Figure 5a shows that at 270 Hz motion is centered on the soundboard, which breaks up into two distinct vibrating areas with a node down the center of the plate, as demonstrated in the computer animations. This particular guitar is of symmetrical construction, and there is equal plate activity either side of the nodal line. Some makers include an angled transverse bar below the sound-hole. This asymmetry has two effects. The unequal motion either side of the nodal line would have a tendency



(a) 268 Hz (b) 436 Hz (c) 553 Hz (d) 628 Hz (e) 672 Hz

(f) 731 Hz (g) 873 Hz (h) 980 Hz (i) 1010 Hz (j) 1174 Hz

Figure 5. Higher modes of vibration of a guitar soundboard.



(a) 307 Hz (b) 366 Hz (c) 385 Hz (d) 399 Hz (e) 509 Hz

(f) 546 Hz (g) 656 Hz (h) 695 Hz (i) 810 Hz (j) 1012 Hz

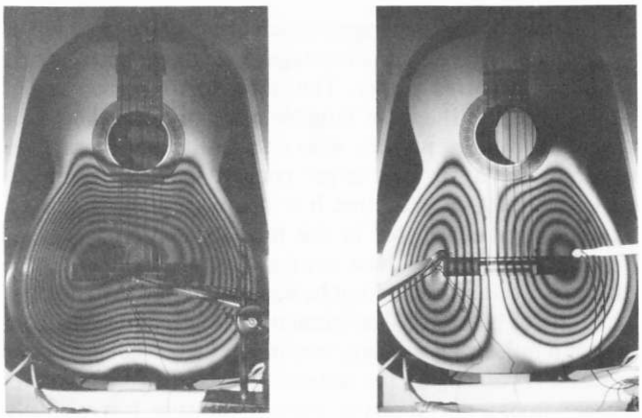
Figure 6. Higher modes of vibration of a guitar back plate.

to increase sound radiation from this mode. However, because the nodal line tends to move it modifies the coupling between the strings and the body, and enhanced radiation can be achieved only if strong coupling is maintained. As with most variations from standard construction, musically relevant changes to the action of the instrument are not guaranteed. At 430 Hz the plate divides along its length. The strings lie on a vibrating part of the plate and therefore they couple to this mode to take advantage of this strong radiator. Note that the back is also vibrating (this can be seen through the sound-hole). The back is picking up energy radiated from the sound-board and vibrating in one of its modes. This soundboard mode also couples to one of a number of air modes which involve air vibrating back and forth inside the cavity, in this case between the upper and lower bouts [10], [11]. As the frequency increases the plate divides further. At 550 Hz there are three vibrating areas, but these increase to 10 by 1200 Hz. The strings do not couple very easily to these higher modes. There is roughly one mode every 100 Hz, so we might expect to measure 20 different vibration patterns up to 2000 Hz. Beyond that the modes are less distinct and tend to merge into each other.

Figure 6 shows a collection of back-plate modes. In many respects, the vibrations are similar to the soundboard, except that the different strutting patterns tend to localize the vibrations in different regions. When playing the instrument, these modes are activated by energy flowing round the structure from the soundboard [10]. The vibrations tend to be damped by contact with the body of the player. The use of dense materials tends to limit the vibration amplitudes of the back vibrations, thereby limiting the energy lost by this route.

It is interesting to look briefly at the influence of the strutting on the vibrations of the plate. Figure 7a shows the effect on the first soundboard mode of relieving the transverse bars on either side of the sound-hole. Contrary to common belief this does not significantly extend the vibrations into the upper bout. However, the cut-outs reduce the stiffness of the plate at this strategic place and the mode frequency is lowered. This is often not desirable and might require a thicker plate to compensate for the reduction in stiffness. In this same instrument, there was also a small bar running under the treble side of the bridge. This introduces asymmetry into the plate. Figure 7b shows clearly how the asymmetry has pushed the nodal line to the left towards the sixth string. What is evident in all of the results shown so far is that stiffening elements which lie across the grain (across the width of the guitar) have a greater influence on the shapes of modes. The fan struts do not appear to influence the shapes of modes until very high frequencies. The fan struts are therefore important to achieve the correct balance between longitudinal and transverse stiffness of the plate, but their precise number and distribution are of less importance [6].

Investigations of a large number of instruments show that all guitars of "standard" construction share the basic features discussed above. Many "novel" or non-standard construction techniques produce similar mechanical action. What are important are the detailed differences, however small, because it is these which distinguish one instrument from another or the great from the mediocre. The body of the guitar is a mediator between the string (and the player) and the outside world. Efficient transfer of energy from the strings depends



(a) 85 Hz (b) 195 Hz

Figure 7. The effects of modifications to the internal strutting (see text).

firstly on good coupling to the body and secondly on good radiation efficiency of the body modes. Some of our recent studies have highlighted the importance of several low-order modes (see Figure 3a, 3c and 3d) which appear to be responsible for radiating much of the guitar's energy at all frequencies [7], [12]. The first of these modes is very robust, and its coupling efficiency to the strings is guaranteed irrespective of construction. Efficiency can be maximized by aiming at a compromise between stiffness in the soundboard and a low mass, although the interaction between the sound-board, back plate and air cavity complicate the issue [9]. This is why the lightweight, fan-strutted soundboard has found universal acceptance in the modern concert guitar. The shapes of the other two modes can vary significantly, and coupling efficiency and radiation efficiency are highly dependent on construction. A better understanding of the control of these modes might help us to comprehend how to systematically ensure "better quality" instruments or at least to maintain consistency in manufacture.

ACOUSTICAL DEVELOPMENTS

In the previous sections, we have seen how the sound quality of a guitar depends on the excitation of the strings and the vibrational properties of the wooden body. In fact, all stringed instruments are governed by similar principles and work in a similar manner. A violin, for example, has modes of vibration of the body which share many of the features found on a guitar [3]. The arched plates of a violin do not lead to a fundamentally different mechanical action; the arching, the different general dimensions and different plate thicknesses used in violins simply give rise to mode shapes and mode frequencies which are different in detail from those found in typical guitars, and it is these detailed differences which distinguish the instruments acoustically. There have been no developments of the classical guitar which have fundamentally altered the way in which it works.

There have, of course, been many changes to the structure of the guitar during its evolution. Consequently, the sound quality of the modern guitar has little in common with its earlier counterparts. The most obvious changes relate to stringing and to the general proportions of the instrument and the thicknesses of the plates [13]. Leaving aside the musical implications of these changes, which are very far-reaching, it is clear that the acoustical advantage of the modern instrument is one of increased power. The quest for increased power output is one of the more tangible goals of the maker. This quest is driven by players, who constantly find themselves required to play in ever-larger concert halls or having to compete with large orchestras. It is these sorts of developments which will be considered in this final section.

Before discussing these matters further, we should note that power output should not be equated simply with quality. The tone of a "louder" instrument is usually different from that of a quieter instrument, and might be considered better or worse depending on the tastes of the player. Furthermore, power output is not an easy quantity to measure. It is relatively easy to modify the structure so as to increase the initial intensity of the sounds radiated by a guitar, but, as with any modification, a change in one acoustic variable leads to changes in related variables. Thus, an increase in initial intensity is usually accompanied by a decrease in the duration of the note (that is, a more rapid decay). A more intense but short duration sound is not necessarily perceived by the ear and brain as being "louder." Acoustic power is not, therefore, a direct measure of subjective "carrying power."

One obvious way to increase the power output of an instrument is to increase the vibrating mass of the strings [14]. This can be achieved by increasing the vibrating length of the string or by increasing its density or diameter. However, for the same pitch, we then require a higher tension, and it is only in recent years that modern technologies have enabled strings to be made reliably with much higher breaking strains. The synthetic materials used in the manufacture of modern strings have different internal damping from the old gut strings. Nylon strings thus sound different from gut strings. Most players fully accept these changes in the sound and therefore take advantage of the better reliability and accuracy of modern synthetic strings. Most young performers, in fact, will never have played on gut strings.

Although high tension strings potentially create more sound, the increased stress on the soundboard, if unchecked, can lead to distortion of the body or even to premature structural failure. Consequently, there have had to be changes in the construction of the instrument. If the soundboard had simply been made thicker, the body itself would have become less efficient at converting the motion of the string to audible sound. So the natural development has been to create instruments with larger bodies and thicker, braced plates. The balance between plate size and stiffness must, however, be carefully regulated if the acoustical advantages are to be maximized. There is no reason to believe that this balance has been optimized in the modern instrument.

Earlier instruments, such as lutes and vihuelas, tended to have much lighter bodies. Thus, although the strings were shorter and of lower tension than in the modern instrument, the lightweight construction created a body which was easier to set in vibration and they produced a comparatively large sound. The differences between modern and early instruments are best made by comparing measurements on these two types of families. I have thus examined the vibrations of a replica vihuela. This particular instrument was made by the English maker Martin Fleeson in 1978. It is not a copy of any particular instrument, but it embodies typical features of an early instrument. It has a string length of 600 mm, a body length of 440 mm and body depth of about 70 mm. The upper bout, waist and lower bout dimensions are 235 mm, 215 mm and 275 mm respectively, so the area of the plates is considerably smaller than in a modern guitar. The string tensions are roughly one third those found in a modern instrument. Measurements were made of the admittance of the instrument (this is a measure of the ease with which the instrument is set into vibration at different frequencies), as well as using holographic interferometry to photograph the modes of vibration. For a number of technical reasons these photographs are not of sufficient quality to reproduce here. However, mode shapes and frequencies have been summarized in Figure 8. This figure compares results from the vihuela with data from the guitar described in the previous section. The figure shows clearly that the vibrations of the two instruments are similar in form and frequency. The increase in mode frequencies which would have been expected as a result of the smaller dimensions of the body has been offset by the decrease in thickness of the plates.

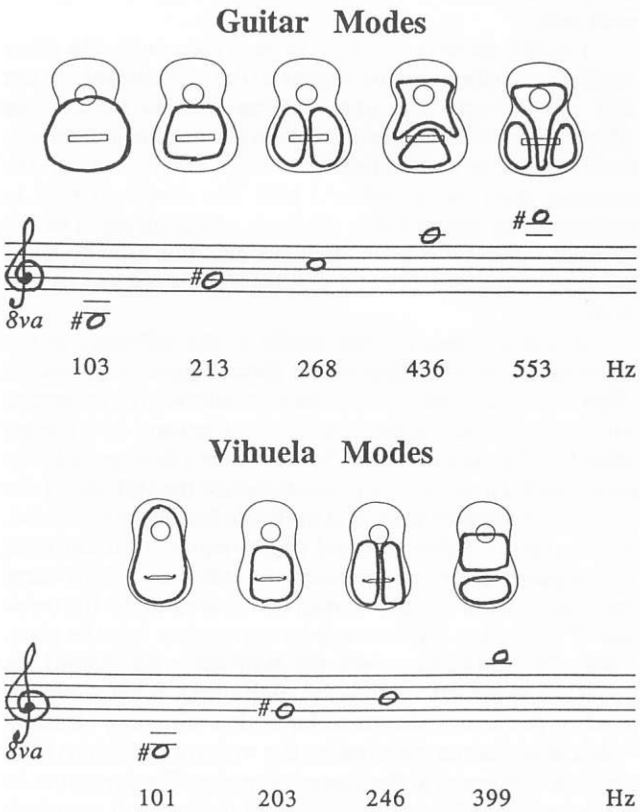


Figure 8. Comparative mode frequencies of a modern classical guitar and a replica vihuela.

The first resonance of the vihuela occurred at 101 Hz. As in the guitar, this involves cooperative motion of the soundboard, the back plate and the air inside the cavity of the instrument. The frequency of this mode depends partly on the volume of the cavity and the open area of the sound-hole. The small volume of the cavity would tend to increase the resonance frequency [11], but the smaller aperture of the sound-hole, which was half-filled with carving, helps to keep this frequency low. The smaller aperture tends to inhibit radiation from the sound-hole, however. The next two modes are similar to those found in the modern guitar. The fourth resonance occurred at about 400 Hz, at which frequency the plate rocks about a nodal line running almost exactly along the bridge. Coupling to this potentially important mode is thus weak. In conclusion, therefore, we see that the vihuela and guitar work in a very similar way, but one has only to play on the vihuela to demonstrate that it has a "smaller sound" than that which we have come to expect from a modern guitar. The lower tension strings and the smaller plate area of the vihuela contrive to create less overall sound, even though the lightweight soundboard of the vihuela had a higher input admittance than the guitar (at least in the low frequency range), and it is thus readily set in motion by the strings. The duration of the sound was also comparatively short because the lightweight construction tends to suck energy away from the soundboard to the back and sides, where energy is damped and lost through contact with the player rather than converted to useful pressure waves in the surrounding air.

One aspect of construction which the above study highlights is that a low vibrating mass, or *effective mass*, of the soundboard encourages higher power output. Unfortunately there is no simple relationship between the actual mass of the soundboard and the effective mass of individual modes. Effective masses can vary from a few ten of grams for the fundamental mode (Figure 3a) to tens of kilograms when the nodal line lies near to the bridge area. However, light construction favors a low effective mass for the fundamental soundboard mode, and this mode is one of the most important acoustically [7], [15]. The effective mass can be lowered by thinning the plate, but thinning the plate actually has a more dramatic effect on the plate's stiffness (the latter is proportional to the cube of thickness). Statically, the plate then becomes too weak to support the strings, and dynamically, we find that mode frequencies drop and modes bunch together and fail to provide acoustical support throughout the entire playing range. Strutting the plate is one technique which can be used to increase the stiffness-to-mass ratio to the soundboard. The cross braces, bridge and fan struts are thus strategically placed to increase the stiffness of the plate whilst allowing the effective mass of the principal modes to be kept as low as possible. Makers are known to exercise great care in the selection and preparation of materials [8], [16]. The intrinsic stiffness of wood, measured in terms of the Young moduli along and across the grain, is governed not only by the growing conditions of the wood but also by the way it is cut. The cross-grain stiffness of wood drops alarmingly when the grain is not perfectly quartered. Even a few degrees off the quarter can substantially reduce the stiffness of the plate, which must then be left thicker. Similarly, wood rendered from a tree which involved spiral growth, in which the wood fibers do not lie parallel to the surface of the board, shows a significant reduction in stiffness along the grain. Again, the board would have to be left thicker. A thicker, more massive soundboard produces less power output. The distinction between good and excellent instruments is extremely small, and it is clear that the use of "optimum" materials are essential in the production of the finest instruments.

There are other ways in which the effective mass of the soundboard can be lowered. Cedar, for example, has a greater stiffness-to-mass ratio than spruce, and it is now commonly used in the production of highly prized instruments. The different mechanical properties of the material, however, produce a characteristically different sound. Other makers are experimenting with man-made materials or novel construction methods. I was interested recently to learn a little more about the work of Australian luthier Gregg Smallman [17]. He uses extremely thin cedar soundboards with very low effective masses, but he maintains normal resonance frequencies by employing a system of lattice braces on the underside of the plate. This lattice adds general stiffness and prevents twisting until high frequencies, but to maximize the stiffness-to-weight ratio of the plate, the lattice braces are made from balsa wood reinforced with carbon-fibers. Conventional wooden braces would not be able to give the same advantage. He also uses heavy, laminated back and sides which minimize wasted energy flow to the player's body. These are undoubtedly more powerful instruments. However, the low effective mass and increased radiation efficiency tend to produce a more "percussive" sound from the strings, partly because of an increase in the body noise emitted during the transient. The sound is not liked by all players, but these instruments go some way towards satisfying the demands of players who wish to perform in large concert halls.

Bridge design is another area which might be exploited by makers to enhance sound radiation from the instrument [4], [5], [18]. The bridge is not simply an appendage on which to fasten the strings. It is, in fact, an important component of the strutting system, adding considerable stiffness across the weakest part of the soundboard. The mass, stiffness and general proportions of the bridge can be modified to alter the relative amount of coupling between the strings and specific body modes. These modifications can be made within the confines of what is accepted as "normal" bridge design.

CONCLUSION

In summary, I hope that I have demonstrated that the instruments of the extended guitar family all work in a similar way. I must stress again, however, that it is the precise details of the instrument's vibrations which are important. It is these detailed differences, sometimes apparently insignificant, which distitnguish one instrument from another or make one instrument supreme. There is no unique "formula" for ensuring good response. The tone quality of a guitar is not governed simply by the outline shape or the particular arrangements of the fan struts; if this was the case, instruments would be easy to copy. Instead, the mechanical action is governed by a complex equation involving the subtle interaction of the dimensions of the component parts and the precise material properties of these parts. Ensuring consistency, which is one of the most difficult aspects of the manufacturing process, requires makers to reproduce instruments having identical vibrational and radiative properties. Because no two pieces of wood are alike, even when they are taken from the same tree, the maker has to fashion each piece of wood in an individual way to exploit its maximum advantage.

Makers will continue to innovate. If for no other reason, this is a necessary part of the process of learning how to accommodate for variations in materials. As well as traditional methods, new materials and automated methods of manufacture are now available. Only time will tell whether these will help to "improve" the quality of instruments or at least improve the consistency of their manufacture. Most of the lasting developments which have occurred in the guitar have come about in response to better string materials or the musical demands of players and composers. Change should not be driven by technology or economics. One of the greatest difficulties to be faced is in defining what changes would be desirable. There is not, and never will be, any such thing as an "ideal" guitar sound. Radical changes in materials or construction which offer genuine musical advantage will, no doubt, be universally adopted. Unfortunately, all too many innovations in guitar design are based upon a false premise or false expectation, and these sorts of innovations are doomed to failure or to become the curiosities of future generations. I believe that science may be able to help in the natural development process by increasing awareness of the precise mechanisms involved in sound production in the instrument. At the end of the day, however, there is no substitute for the sensibilities of the skilled craftsman who has learned through long experience how to extract the required vibrations from carefully chosen and carefully fashioned pieces of wood. It is these makers who hold the key to the future prosperity of the instrument.

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ABOUT THE PAPER

The preceding paper was presented at the Cordoba Guitar Festival in July 1992. The Festival acts as a focus for all manner of guitar activities, catering to players, makers and listeners in this delightful, historic city. As well as master classes and performances of classical, flamenco and contemporary music by some of the world's most renowned guitarists, the Festival hosts a guitar-making course run by José Romanillos. Sr. Romanillos, a maker of exceptionally fine instruments, uses traditional methods and techniques, which are based firmly on those employed by Torres, the "father" of the modern guitar. It was in connection with the latter course that I was invited to present a paper covering the research work carried out in Cardiff on the acoustics of the guitar. The paper was presented as part of a study session on the history of the guitar *(IV Journadas de Estudio Sobre Historia de la Guitarra)* and published in a Spanish translation by María José Chamorro Peláez in the book *La Guitarra en 'a Historia IV: Cuartas Journadas de Estudio Sobre Historia de la Guitarra.* The greatest reward, however, came from the participation in the guitar workshop and the many interesting discussions which were raised amongst the makers.

I took as a theme the acoustical development of the guitar, though I must confess that it is basically a tutorial on the mechanics of the instrument. The paper was written with the non-technical reader in mind and it thus incorporates discussions of very basic concepts. I make no apologies for not having edited the paper for its inclusion in the Catgut Journal. There is always someone new to the subject who appreciates being "reminded" of these matters, and, in the spirit of our Journal, I would rather interest one or two makers even at the expense of boring some of the more-seasoned acousticians. The paper results directly from the research work at Cardiff, which aims to establish relationships between the construction and sound (dare I say sound quality) of guitars. The paper is really directed at guitar makers with a view to stimulating their thoughts about how they might control or modify construction to ensure quality control in manufacture. I would hope, however, that players and makers of other instruments will also find some of the concepts of interest.

I would particularly like to thank Sr. Eusebio Rioja Vazquez for the invitation to participate in the Festival and for his permission to reprint this paper in English.